

Frequency Support using Doubly Fed Induction and Reluctance Wind Turbine Generators

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Abstract

This paper presents the comparative computer simulations of a commercial doubly-fed induction generator (DFIG) and an emerging brushless doubly-fed reluctance generator (BDFRG) for grid-connected wind turbines in terms of frequency support based on the inertia emulation and blade pitching de-loading. The BDFRG features the low operation and maintenance cost by using a fractional inverter, and offers the high reliability of brushless structure with a simpler, more compact 2-stage gearbox design whilst still ensuring competitive performance to its popular slip-ring companion. The implemented benchmark is carefully designed to ascertain the relative capabilities of the two wind turbine generator technologies in providing this ancillary service. The results reveal that in spite of the fundamentally different operating principles, the DFIG and the BDFRG are highly aligned from the viewpoint of power system applications.

Keywords: Wind Power, Doubly-Fed Machines, Ancillary Services, Frequency Stability, Virtual Inertia.

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24 **Nomenclature**

25	D_F	De-loading ratio
26	H_d	On-line inertia constant
27	$f_{drop_{max}}$	Full support frequency threshold
28	f_{low}	Frequency safe margin
29	f_o	Nominal frequency
30	P_c	Actual conventional generation in AC area
31	P_c^o	Installed conventional generation in AC area
32	P_{WF}	Wind farm generation
33	P_{ref}^o	Active power reference
34	$T_{e,m}$	Wind turbine electrical, mechanical torque
35	T_{gen}	Conventional generation torque
36	T_{ref}^o	Nominal reference torque
37	D_g, D_l	Dynamic load model parameters
38	J	Moment of inertia
39	K_{ex}	Extraction factor
40	R	Droop of aggregate generator
41	ΔP	Power mismatch
42	BDFG	Brushless Doubly-Fed Generator
43	BDFIG	Brushless Doubly-Fed Induction Generator
44	BDFRG	Brushless Doubly-Fed Reluctance Generator
45	DFIG	Doubly-Fed Induction Generator
46	DFMs	Doubly-Fed Machines

47 KE Kinetic Energy
48 MPT Maximum Power Tracking
49 SGs Synchronous Generators
50 RoCoF Rate of Change of Frequency
51 TSOs Transmission System Operators
52 WFs Wind Farms
53 WS Wind Speed
54 WTGs Wind Turbine Generators

55 **1. Introduction**

56 The foreseen proliferation of distributed generation, and the accompanying
57 disconnection of conventional power plants, might seriously threaten the power
58 system voltage and frequency stability [1, 2]. Consequently, TSOs have been
59 updating the grid codes to incorporate the new demands from classical SGs and
60 WFs, while the manufacturers of WTGs are competing to assure the compliance
61 of their products with the latest grid integration regulations, including the abil-
62 ity to participate in the frequency regulation [3]. The reduced global inertia is a
63 critical challenge for the system stability to face with the increasing penetration of
64 WFs in large power networks or island grids [4] [5]. To this extent, several control
65 methods have been proposed with an incentive to allow the WTG to successfully
66 tackle the frequency decay by imitating the inertia and primary responses of SGs
67 in power stations [3, 4]. Clear and well defined technical and legal rules and proto-
68 cols are essential to avoid possible conflicts and malfunctions when such support

69 methods are applied to large scale to ensure a smooth coordination between power
70 systems and WFs during and shortly after frequency events [6].

71 This can be accomplished by maintaining a certain power reserve, or by re-
72 leasing a portion of the stored KE in the WTG rotational parts [7]. The standard
73 approaches taken are turbine blades pitching (e.g. de-loaded operation), emulated
74 KE extraction (i.e. synthetic inertia), and tip-speed control [8]. Alternative inno-
75 vative strategies have also been devised and studied recently [9]. The effectiveness
76 of all these procedures is contingent upon the WTG responses to sudden changes
77 in WS and/or torque (power) reference stipulated by the controller to produce the
78 aimed power surge and help curtail the incurred frequency fluctuations in the best
79 possible manner. Quantitative metrics of frequency support capabilities of various
80 WTGs and WFs using different methodologies have been put forward in [10].

81 Some recent work touched upon the impact of the controllers gains to pro-
82 vide pitch de-loading and virtual inertia. The study derived the root-loci and
83 produced time simulations of a wide range of the involved controllers parame-
84 ters (e.g. pitching system, torque control and frequency support) to investigate
85 whether the control system stability was aligned to the improved performance of
86 frequency response [11]. The main challenges facing de-loading and KE extrac-
87 tion are continuous curtailment of wind power and post-event recovery respec-
88 tively. The amount of non-supplied energy due to de-loading techniques could be
89 estimated according to the expected load curtailments. These curtailments will
90 have an evident impact on frequency response as well as the financial aspects of
91 system operation and dispatching. Simplified mathematical representation of the
92 power system could be applied to calculate analytically the system inertia and
93 available primary reserve of WFs [12]. Meanwhile, the recovery stage (i.e. post

94 frequency drops declared clear) could trigger further frequency drops, as the WTG
95 output is suddenly reduced to start the recovery process, which is a key challenge
96 of KE extraction. This could be mitigated by applying a pre-set shaping function
97 with a ramp reduction in the WTG electrical output. The shaping function was
98 triggered automatically independent of the drop severity when the frequency vi-
99 olated the safe deadband to initiate a step increase in the reference power signal
100 of the WTG [13]. The technology and research challenges classification in con-
101 sidered six main categories of exploitation: frequency deadband, RoCoF, droop
102 control, de-loading parameters, wind turbine level and wind farm-wide. However,
103 the generator technology was not included which identify this area as a knowledge
104 gap that could be tackled by this paper. The same reference has also presented the
105 common designs of the supplementary controls used to apply the different con-
106 cepts of frequency support, and their integrative approach to the holistic controls
107 of the WTG [14].

108 The distinct advantages of high torque density, typically 30% rated power elec-
109 tronics, and inherently decoupled power control, have made the DFIG a widely
110 adopted cost-effective solution for multi-MW wind turbines with restricted vari-
111 able speed ranges (e.g. 2:1 or so) [15]. Nevertheless, the presence of brush gear
112 unavoidably reduces its reliability raising the maintenance requirements, espe-
113 cially off-shore [16]. The BDFG overcomes the above DFIG drawbacks and has
114 been regarded as a viable replacement. Unlike the DFIG, the BDFG has two ordi-
115 nary, distributed 3-phase stator windings of different applied frequencies and pole
116 numbers, and a rotor with half the total number of stator poles for the shaft posi-
117 tion dependent magnetic coupling to occur between the windings, a pre-requisite
118 for the torque production. The rotor can be of special ‘nested-loop’ cage or wound

119 structure (e.g. BDFIG) [17], featuring rather complicated and strongly parameter
 120 reliant control, or modern cage-less reluctance form (e.g. BDFRG) [18] allowing
 121 similar control simplifications of DFIG [15]. The primary (power) winding is di-
 122 rectly grid connected, while the secondary (control) winding is supplied through a
 123 fractional dual-bridge converter in ‘back-to-back’ configuration for bi-directional
 124 power flow as with the DFIG (Fig. 1).

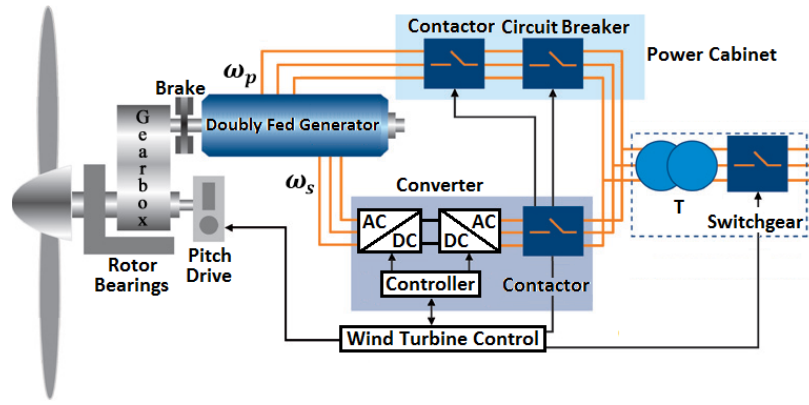


Figure 1: A generic conceptual diagram of the BDFG and DFIG wind turbine for adjustable speed constant frequency grid-connected applications².

125 As the BDFG name reiterates, brushes and slip rings are eradicated, hence
 126 a more robust and maintenance-free construction. Besides, the BDFG is essen-
 127 tially a medium-speed machine, which renders the vulnerable high-speed stage
 128 of a three-step planetary DFIG gearbox redundant, enhancing the reliability and
 129 bringing further economic benefits [16]. These favorable properties are partic-
 130 ularly appealing for off-shore WFs, where the DFIG running costs can be con-
 131 siderable [19]. Moreover, another salient BDFG merit to be pointed out is the
 132 distinguishing low-voltage-ride-through (LVRT) capability, which can be realised
 133 with much facilitated, or completely without, protective crowbar circuitry for the
 134 machine-side converter unlike the DFIG. Such attractive BDFG attributes have

135 been afforded by the proportionally higher leakage inductances and lower fault
136 current amplitudes than the equivalent DFIG having the well-known difficulties
137 to fully satisfy the LVRT pertaining grid codes [19].

138 Similar research to that conducted for the DFIG [15] has been carried out
139 on the BDFRG involving: vector control with voltage [20] or flux (field) space-
140 vector orientation [21] including sensorless operation since an encoder is required
141 for current control in a rotating frame, even though purely sensorless field oriented
142 control is feasible as documented in [22] using the maximum torque per inverter
143 ampere objective. The encoder-less BDFRG operation under power factor field
144 oriented control conditions, as an extension of this experimental vector control
145 research, has been elaborated in [23], direct torque [24] and power control [25].
146 Despite the apparent efforts and significant progress made in this direction, apart
147 from the aforementioned large-scale design studies [26], predominantly small-
148 scale laboratory prototyping has been the focus of attention among investigators,
149 except for the more sizeable BDFRGs reported in [27] and the latest one elabo-
150 rated in [17]. Although the BDFRG has been experimentally proven competitive
151 with the DFIG concerning both cost and performance [28], there is very little
152 documented on its grid integration issues and literally nothing published on the
153 feasibility to assist in the power system frequency control. Instead, the exist-
154 ing literature on the subject has mainly concentrated on the established industrial
155 technologies used for this purpose, the traditional DFIG [29] and/or the perma-
156 nent magnet generator [30]. However, publications on comparative analyses of
157 frequency support potential of these two, or any other WTGs are scarce [31].

²The control winding is on the stator for the BDFG, and on the rotor for the DFIG, but this is not detailed in the figure for convenience.

158 Although the concepts of KE extraction and output de-loading are widely dis-
159 cussed in the literature, the proposed implementation methods are different where
160 the droop de-loading is applied to manipulate linearly to the instantaneous fre-
161 quency deviation. Likewise, the KE extraction is implemented through the tuning
162 of an over-demand parameter, which influences the ratio between optimum and ac-
163 tual torque references. The adopted methods and parameters settings are aligned
164 to enable a reasonable and fair comparison between the impacts of both the WTG
165 technology and the support methods. The key parameters in both methods are
166 selected to be equivalent, such that the de-loading and extraction factors are equal
167 and both controllers have the same frequency deadband and frequency drop limit
168 to release the full reserve. The applied case studies are also designed to consider
169 and emphasize the impact of WS changes either on the dynamics of the WTG
170 or the response of the power system, where the load dynamics are incorporated
171 to cause fine variations on the system frequency. This examines the reactions of
172 the WTG under like-real frequency oscillations when applying different combina-
173 tions of two different generator technologies and two frequency support methods.
174 The exploitation of these aspects is very limited in the literature. Finally, this
175 paper presents a simplified method to estimate the dynamic inertia of the power
176 system under the penetration of wind power. Consequently, this paper will there-
177 fore contemplate on the comparisons of the prominent and forthcoming BDFRG,
178 and the prevailing DFIG capacities to provide such an important ancillary service
179 operating as MW range WTGs.

180 2. BDFRG Model and Operating Aspects

The fundamental angular velocity and mechanical power relationships for the electro-mechanical energy conversion in the machine, showing individual contributions of each winding and assuming motoring convention as default, can be written as follows [32, 33]:

$$\omega_r = \frac{\omega_p + \omega_s}{p_r} = \frac{\omega_p}{p_r} \cdot \left(1 + \frac{\omega_s}{\omega_p}\right) = \omega_{syn} \cdot \left(1 + \frac{\omega_s}{\omega_p}\right) \quad (1)$$

$$P_m = T_e \cdot \omega_r = \underbrace{\frac{T_e \cdot \omega_p}{p_r}}_{P_p} + \underbrace{\frac{T_e \cdot \omega_s}{p_r}}_{P_s} = P_s \cdot \left(1 + \frac{\omega_p}{\omega_s}\right) \quad (2)$$

$$k = \frac{\omega_{max}}{\omega_{min}} = \frac{\omega_p + \Delta\omega_s}{\omega_p - \Delta\omega_s} \implies \Delta\omega_s = \frac{k-1}{k+1} \cdot \omega_p \quad (3)$$

181 where $\omega_{syn} = \omega_p/p_r$ [rad/s] is obtained for $\omega_s = 0$ i.e. a DC secondary as
 182 with a $2p_r$ -pole wound field synchronous turbo-machine, $\omega_s > 0$ for ‘super-
 183 synchronous’ operation, and $\omega_s < 0$ (e.g. an opposite phase sequence of the
 184 secondary to the primary winding) in ‘sub-synchronous’ mode. Therefore, for
 185 the same number of rotor poles, the synchronous speed (ω_{syn}) of the BDFRG is
 186 half that of the DFIG, which implies that the 3rd stage of a gearbox, prone to
 187 high failure rates and hence expensive repairs (foremost at sea), can be avoided
 188 improving the reliability and reducing the WTG downtime as well as the mainte-
 189 nance costs [16]. In the BDFRG case, $T_e < 0$ and thus $P_p < 0$ in (2), so that the
 190 positive power is actually fed to the grid by the primary winding as expected in
 191 the generating mode, while the secondary power (P_s) flow can be bi-directional
 192 subject to the operating speed region as depicted in Fig. 2. Note also that if the
 193 desired operating speed range is 2:1 i.e. $\pm\Delta\omega_s/p_r$ around ω_{syn} , being common
 194 for WTGs, then $k = 2$ in (3) and the maximum secondary frequency turns out to

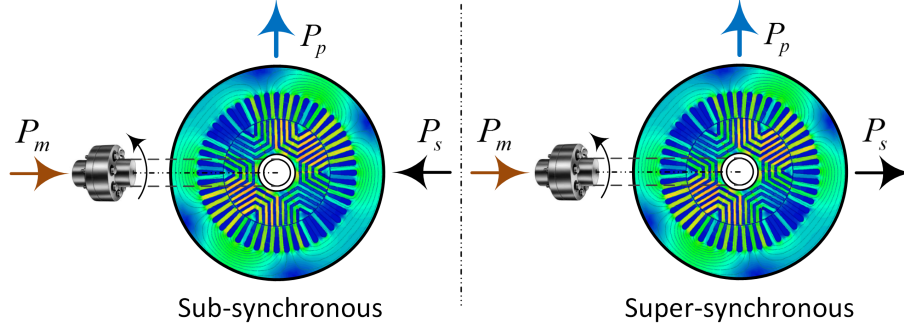


Figure 2: Reference directions of real power flow in the BDFRG windings for the operation below and above the synchronous speed.

195 be $\Delta\omega_s = \omega_p/3$ whereas $P_s = P_m/4$ according to (2). This means that only a
 196 25% rated converter would be ideally needed as with the DFIG wind turbines.

197 The BDFRG dynamic and steady-state models in a $d_p - q_p$ frame for the ω_p
 198 rotating primary winding space-vectors, and a $d_s - q_s$ frame for the ω_s rotating
 199 secondary counterparts (Fig. 3) can be represented as [20–23, 34]:

$$\left. \begin{aligned}
 \underline{v}_p &= R_p \underline{i}_p + \frac{d\lambda_p}{dt} = R_p \underline{i}_p + j\omega_p \lambda_p \\
 \underline{v}_s &= R_s \underline{i}_s + \frac{d\lambda_s}{dt} = R_s \underline{i}_s + j\omega_s \lambda_s \\
 \lambda_p &= L_p (\underbrace{i_{pd} + ji_{pq}}_{\underline{i}_p}) + L_m (\underbrace{i_{sm_d} - ji_{sm_q}}_{\underline{i}_{sm}^*}) \\
 \lambda_s &= L_s (\underbrace{i_{sd} + ji_{sq}}_{\underline{i}_s}) + L_m (\underbrace{i_{pm_d} - ji_{pm_q}}_{\underline{i}_{pm}^*})
 \end{aligned} \right\} \quad (4)$$

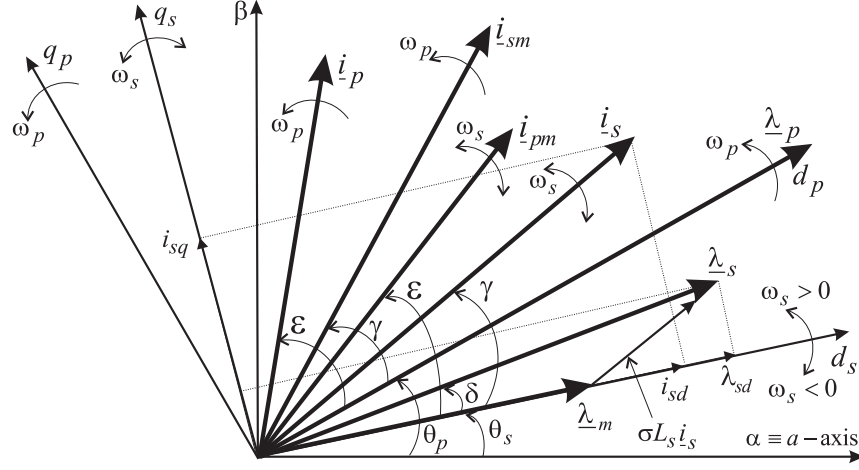


Figure 3: Characteristic space vectors and flux-oriented reference frames relevant for the BDFRG dynamic modelling and control.

The flux equations of (4) can be manipulated as [20–23, 34]:

$$\underline{\lambda}_p = \underbrace{L_p i_{pd} + L_m i_{sm_d}}_{\lambda_{pd}} + j \cdot \underbrace{(L_p i_{pq} - L_m i_{sm_q})}_{\lambda_{pq}} \quad (5)$$

$$\underline{\lambda}_s = \underbrace{\sigma L_s i_{sd} + \lambda_{md}}_{\lambda_{sd}} + j \cdot \underbrace{(\sigma L_s i_{sq} + \lambda_{mq})}_{\lambda_{sq}} = \sigma L_s i_s + \underbrace{\frac{L_m}{L_p} \lambda_p^*}_{\underline{\lambda}_m} \quad (6)$$

where λ_m is the primary flux coupling the secondary winding, $L_{p,s,m}$ are the 3-phase self and mutual inductances derived in [32, 33], $\sigma = 1 - L_m^2/(L_p L_s)$ is the leakage factor, i_{sm} is the magnetically coupled (magnetizing) secondary current vector (i_s) of the same magnitude but modulated frequency (i.e. $i_{sm} = i_s$ in the respective frames), and vice-versa for $i_{pm} = i_p$ as shown in Fig. 3. Notice that i_{sm} , i_p and λ_p in (4) and (5) are in the ω_p frame, whereas i_s , i_{pm} and λ_m in (4) and (6) are in the $p_r \omega_{rm} - \omega_p = \omega_s$ frame given (1). This frame selection is termed as ‘natural’ since the corresponding dq vector components become DC, which are

209 easier to control. The remaining dynamic modeling and operating principles of
210 the BDFRG are detailed in [32, 33].

211 It is interesting that regardless of the unconventional machine design, entirely
212 different basic theory and unusual torque producing mechanism [32, 33], the BD-
213 FRG model described by (4)-(6) in many respects resembles that for the DFIG
214 [15]. In fact, the BDFRG primary and secondary windings, and the associated
215 quantities, play the roles of the DFIG stator and rotor equivalents, respectively.
216 However, the awkward parameter referencing (Fig. 3) and other pertinent struc-
217 tural complexities make the BDFRG model much more challenging to implement
218 and simulate. In addition, the intrinsically modest magnetic coupling (e.g. higher
219 σ values) may compromise the BDFRG transient response to some extent relative
220 to DFIG.

221 **3. Frequency Support Methods and Operation**

222 *3.1. Pitch Droop De-loading*

223 This technique can either be applied as Delta de-loading, when the WTG out-
224 put is de-rated continuously with a fixed relative ratio from the available power, or
225 Balance de-loading where an immobile margin between the MPT operation (e.g.
226 without frequency regulation) and the actual outputs is kept throughout to specify
227 the de-rating profile of interest [35]. This section is concerned with the implemen-
228 tation of the Delta concept in which the reference pitch angle is varied to maintain
229 a predetermined de-loading ratio (D_F) and preserve the nominal rotor speed for
230 a given WS. The active power reference (P_{ref}^o) is decreased by the required D_F
231 according to Fig. 4, and the latter is curtailed regularly through a droop gain until
232 the frequency drop reaches a predefined threshold ($f_{dropmax}$), as illustrated by the

233 supplementary controller design in Fig. 4. For example, when the frequency vio-
 234 lates a certain lower limit (f_{low}), the WTG output could be as depicted, where D_F
 $= 15\%$, $f_{drop_{max}} = 49.5$ Hz, and $f_{low} = 49.95$ Hz.

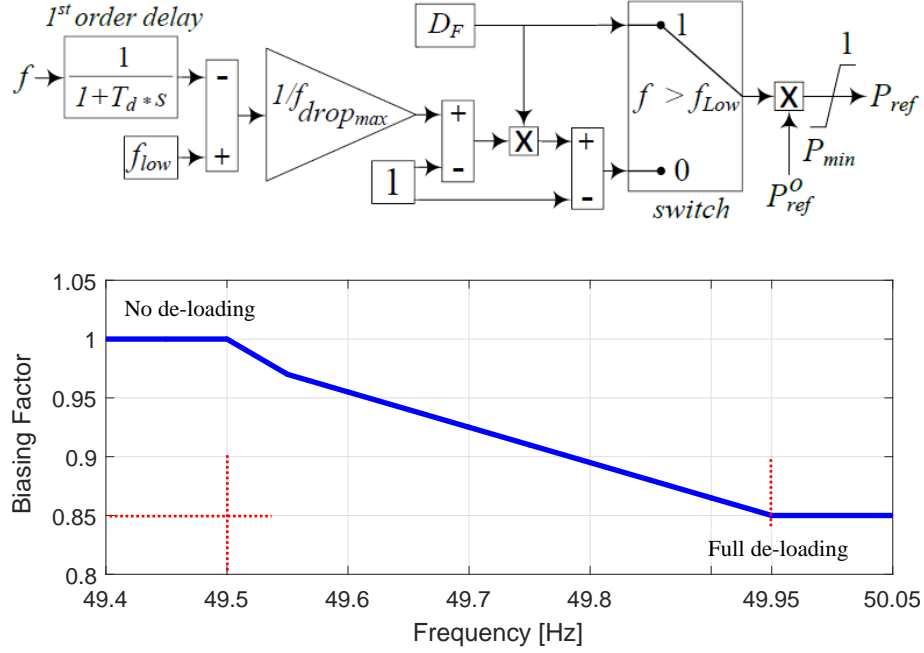


Figure 4: Supplementary controller diagram and curtailment pattern of per unit de-loading based on the incident frequency drop.

235

236 Such a procedure smoothens the frequency response and mimics the gover-
 237 nor droop behaviour of conventional SGs. The de-loading is deactivated at higher
 238 Ws, when the WTG delivers its rated power to mitigate the lost energy. However,
 239 pitching is normally enabled to keep the WTG output and the rotor speed within
 240 the acceptable limits, but at frequency incidents, the pitch angle can be reduced
 241 to allow a temporary WTG overload, which must be compliant with the manufac-
 242 turer specifications to avoid excessive over-heating or other potentially damaging
 243 circumstances for the machine [8].

244 3.2. Kinetic Energy Extraction

245 This approach may be a preferable choice since it does not imply any energy
 246 losses for the normal MPT operation of WFs without frequency control. However,
 247 for the same WS, the power surge is lower compared to the de-loading method,
 248 and there is also high susceptibility to WS conditions both during and after the
 249 frequency event. The scheme relies on the rise of reference torque (T_{ref}) beyond
 250 its nominal value (T_{ref}^o). Hence, the higher electrical demand than the available
 251 mechanical input forces the WTG to extract some of its KE in order to secure the
 252 necessary power support. The extraction factor (K_{ex}) is governed by the severity
 253 of the frequency drop through a droop response by analogy to the de-loading
 method ($1 \leq K_{ex} \leq 1.15$) as shown in Fig. 5. The KE extraction process halts

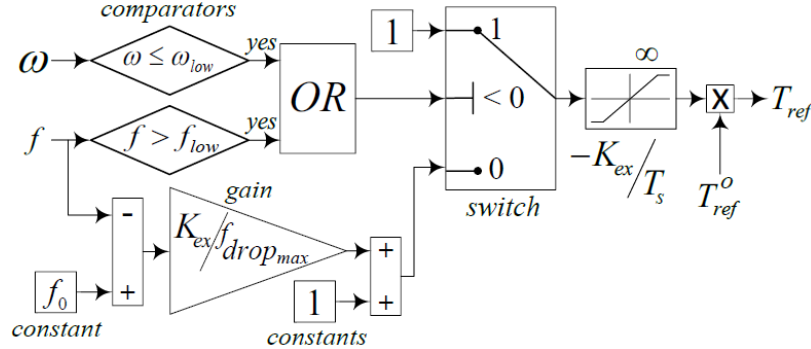


Figure 5: Subsidiary controller schematic of the KE extraction method.

254 when the rotor speed (ω) reaches a predefined lower threshold (ω_{low}). This method
 255 is disabled in case of severe WS drops, which are unlikely to happen, as there
 256 is no back-up source of energy to maintain the supportive power surge, and it
 257 also puts the WTG under the risk of complete halt. The post-event stage is also
 258 critical where the WTG accelerates to recover the nominal rotor speed, implying
 259 a reference torque that is less than the nominal value.
 260

261 3.3. WTG Modeling and Control

262 The auxiliary control algorithms from Figs. 4 and 5 are incorporated into the
 263 realistic detailed DFIG (Type 3) NREL[®] model from the Simulink[®] library as
 264 outlined in Fig. 6 [36]. The replica dynamic model for an equally rated BDFRG
 265 with independent real and reactive power control similar to DFIG [20, 34], and an
 266 optimised ‘ducted’ rotor design (Fig. 2) [18, 26, 37], has been built by employing
 267 the same GE[®] wind turbine so that useful comparative performance evaluations
 of the two WTG technologies can be made.

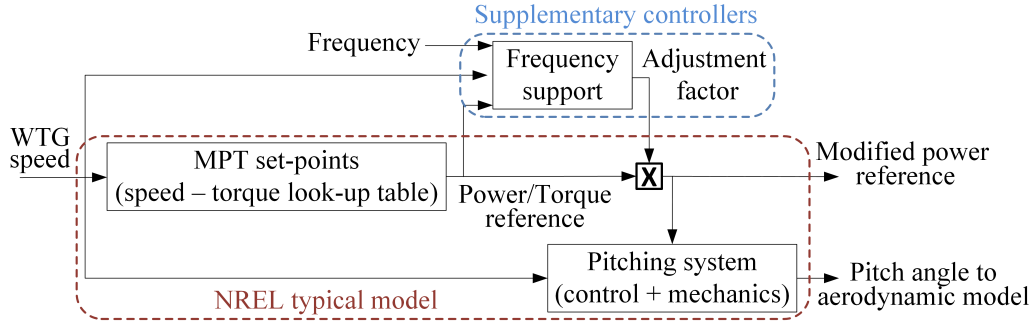


Figure 6: A generic block diagram of the upgraded NREL[®] WTG model [36] with the integrated supplementary frequency controllers.

268
 269 The developed supplementary controllers are also suitably configured to al-
 270 low a fair comparison between the underlying frequency support concepts using
 271 the measured frequency input signals to trigger control actions. Furthermore, the
 272 other key parameters in both methods are likewise selected to be identical for ei-
 273 ther WTG. For example, the de-loading and extraction factors are equal, and both
 274 controllers have the same frequency drop dead-bands and limits to release the
 275 full reserve. The WTG specifications and per-unit values used for the simulation
 276 analyses are summarised in Table 1.

Table 1: The parameters of the DFIG and BDFRG wind turbines

Parameter	DFIG	BDFRG
Rated power (MW)	1.5	1.5
Line voltage (V), frequency (Hz)	690, 50	690, 50
Rated speed (rev/min)	1800	600
Stator, rotor poles	4, 4	8/4, 6
Power winding resistance (pu)	0.0073	0.022
Power winding leakage inductance (pu)	0.1766	0.2519
Control winding resistance (pu)	0.0052	0.0446
Control winding leakage inductance (pu)	0.1610	1.1021
Magnetizing (mutual) inductance (pu)	2.9913	4.4084
Rated wind speed (m/s)	13	13
Gearbox stages/ratio	3/90	2/30
Drive-train inertia constant (s)	4.74	5.2

277 Note, however, that while the frequency regulation strategies under considera-
278 tion have been intensively investigated and applied in the literature [38], whereby
279 the corresponding implementation procedures used in this paper are inevitably
280 different when the droop de-loading ratio is manipulated in response to the fre-
281 quency deviation as shown in Fig. 4. Besides, the KE extraction is achieved by
282 appropriate tuning of the over-demand parameter (K_{ex} in Fig. 5), which influences
283 the ratio between the optimum and actual torque references.

284 4. Studies of Wind Speed Effects

285 The following subsections examine a frequency scenario for step-changes of
286 average WS and realistic wind profiles, and the response of the proposed methods
287 and machines to a certain frequency test signal. The WS fluctuating nature is a

major challenge facing wind energy as a provider of frequency support, hence it is important to exploit its impact when WS changes while the WTG/WF is providing frequency support. The impact of WS is also relevant to the comprehensive comparison between the two machines where the input mechanical power changes according to incident WS. Moreover, the proposed controls have certain modes of operation to mitigate the negative influence of WS steep drops on the provided support. Therefore, this paper tests the proposed methods and machines under a steep WS drop simultaneously with a frequency event. In this section, a test frequency signal is applied to the controls of the WTG, where the frequency drops by $f_{drop_{max}} = 0.5$ Hz from its nominal value (f_o) linearly within 1 s as shown in Fig. 7, which means that the RoCoF is -0.5 Hz/s.

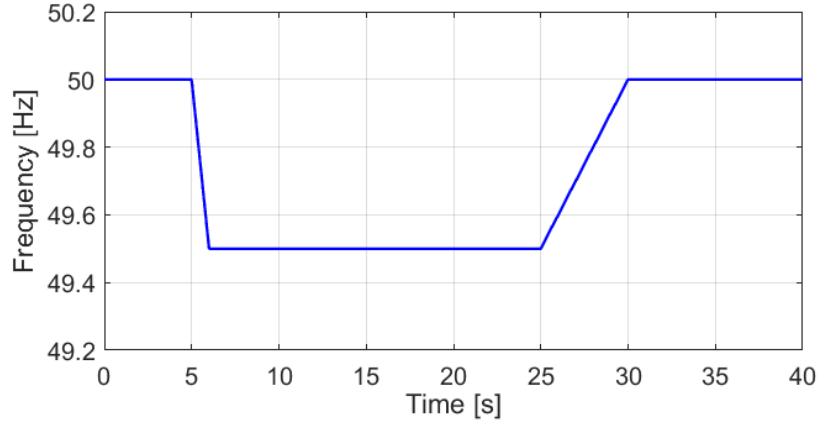


Figure 7: The applied frequency test signal complementary to Fig. 8 and Fig. 9.

298

299 This is inspired by the common requirements of grid codes [39]. Afterwards,
300 at $t = 25$ s the frequency gradually recovers to its nominal value with a rate of
301 change of 0.1 Hz/s. Thus, the WTGs response to frequency dips, and not minor
302 oscillations caused by mild load variations, is one of the main concerns of this

work. In order to enable better capturing of the WTG dynamics even under turbulent winds, the sampling rate of 1 s is chosen for the applied intermittent WS conditions.

4.1. Step Responses

Two sudden WS changes are initiated at $t = 15$ s (e.g. from 8.2 m/s to 7.1 m/s) and $t = 22$ s (e.g. a rise of 0.5 m/s). The power waveforms in Fig. 8 confirm that the normal (i.e. no frequency event) WTG output is reduced in case of the de-loaded method, while the KE extraction counterpart follows the MPT trajectory providing a sustained power surge. The worst power dip occurs after the stored KE is exhausted with the WTG speed reaching its lower threshold as in Fig. 8. The zoomed image frames are integrated to the main figures to enhance the visualization of some reflective dynamics in order to evidence the differences between the waveforms amongst the two WTGs without compromising the visuals of the full simulation span.

The WS drop makes the WTGs to temporarily divert away from the nearly nominal speed as illustrated in Fig. 8. During the frequency recovery, it takes about 25 s for the WTGs to regain the inception steady-state conditions due to the inertia of the rotating masses, and the increasing pitch angles required to restore the de-loaded operation. On the contrary, the KE extraction method does not imply such long transients with relatively high speed deviations for modest WS fluctuations, mainly because the pitch angle is not deployed. The speed recovery relies on the WS prior to the support provision and the attained drift during the frequency event, where it reaches 0.63 pu. In spite of the continuous variations in the available wind power, which are largely dictated by the WTG aerodynamics and rotor speed controllers, the electrical torque (T_e) accurately follows the me-

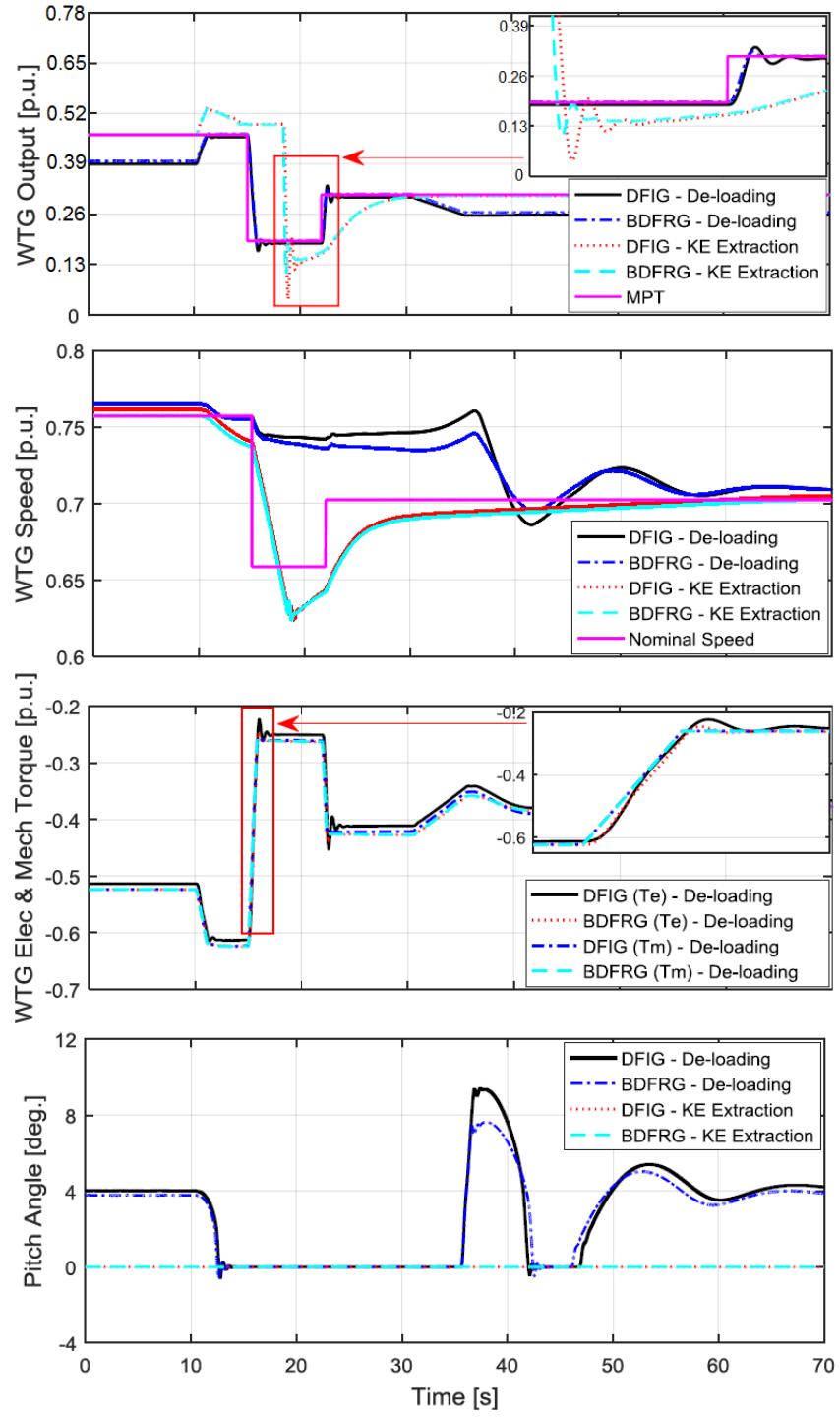


Figure 8: WTGs response to WS step changes for the two support methods.

chanical (T_m). A quick torque response to the very steep change induced by the sudden WS reduction is noticeable from the respective sub-plot in Fig. 8. It is also visible that a generally good matching of the torque waveforms is slightly better for the BDFRG, while the WTGs experience minor oscillations before reaching a new steady-state point with the de-loading method being applied.

The results in Fig. 8 suggest a very close overall performance of the two WTGs, the BDFRG exhibiting a marginally slower response when the pitch angle is recovering to its non-zero value after the frequency transient. This is manifested through the WTG speed under the de-loading method, and it is believed to predominantly come from the somewhat higher inertia of the BDFRG drive train. To achieve the DFIG de-loading level, a lower pitch angle is needed for the BDFRG (e.g. the respective peak values are $\approx 7^\circ$ and 10°), which may count as a merit since the mechanical stresses exerted on the pitching mechanism should be reduced as much as possible.

In summary, the sustainability of the WTG output under the KE extraction method conditions is highly related to the initial WS and the WTG inertia. Conversely, the de-loading strategy does not imply any recovery periods, but the output reduction process is naturally smooth via pitch control effects. In addition, the applied droop pattern ensures the return to the normal de-loaded operation without negative implications.

4.2. Natural Wind Speed Profile

True WS measurement data with an average of about 8 m/s are used to investigate the comparative WTGs performance under the intermittent WS conditions. The WTG output characteristics presented in Fig. 9 are generally sub-optimal for the de-loading method, however, the desired de-loading ratio is not fully achieved

353 as the pitch controller is not able to track all the intended WS fluctuations. Imple-
 354 menting the support method makes the WTG to attain the available MPT output.
 355 The KE extraction technique has proven capable of providing sustainable support
 356 (but with a lower magnitude compared to the de-loading method at medium and
 357 high WSs) as highlighted in Fig. 9. The additional power surge is kept constant
 358 until the depletion of the stored KE stops to avoid the WTG deceleration, evi-
 359 denced by the decreasing speed plots in the same figure, due to the imbalance
 360 between the turbine (T_m) and generator (T_e) torque. The amount of supportive en-
 361 ergy is higher than with the de-loading method, because the WS drop emphasises
 362 the benefit of the KE extraction approach. The intermittent WS profile screens the
 363 dynamics of both machines, hence their very similar responses. It is also shown
 364 that a large inertia and slow responses curtail the WTG ability to match the op-
 365 timum rotor speed for a given WS at each time step. However, the deceleration
 366 impact caused by the KE extraction method is evident during the frequency tran-
 367 sient and as a consequence the WTG attempts to maintain a fixed power surge
 368 according to Figs. 4 and 5.

369 The results in Fig. 9 of comparing the T_e variations of the two generator tech-
 370 nologies and the two support methods reflect the minor deviations between the
 371 two generators. However, when the WTG reaches the threshold rotor low speed
 372 which halts the KE extraction process, the DFIG experiences a sharper transient
 373 response compared to BDFRG, which is further clarified through the employed
 374 zoom in frame. It can be also noticed the steeper transients in case of droop pitch
 375 de-loading compared to KE extraction method due to the continuous variations of
 376 reference pitch angle to maintain the required de-loading ratio. Meanwhile, the
 377 responses for either WTG are nearly overlapping. The pitch angle dynamics con-

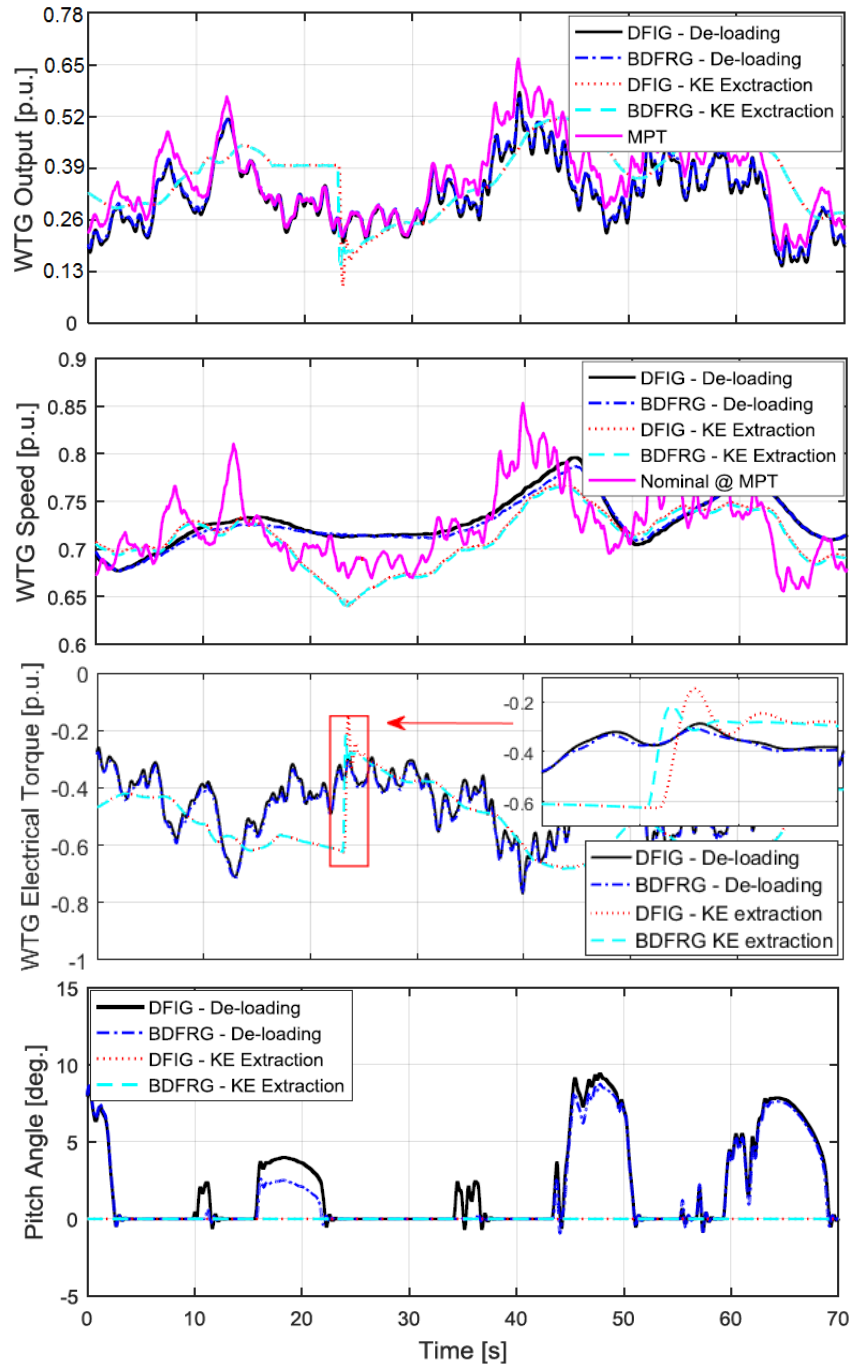


Figure 9: WTGs response provided by the two support methods for a realistic wind speed profile.

378 firms that the de-loading exerts higher stresses on the WTG pitching system than
 379 the KE extraction method, which does not require any additional pitching and
 380 where at an average WS, the pitch angle is zero at all times. The BDFRG ensures
 381 slightly reduced pitch angle changes than the DFIG by analogy to the previous
 382 case study in Section 4.1.

383 5. Analysis of Power System Frequency Response

The considered benchmark is composed of an aggregate synchronous area and installed conventional generation capacity (P_c^o) feeding a composite load as shown in Fig. 10. The AC area inclusion is intended to adequately represent a medium scale power network with an average vulnerability to the frequency fluctuations, which can be modelled as [29]:

$$\dot{f} = \frac{P_c + P_{WF} - P_L - (f - f_o) \cdot (D_l + 4D_g f \pi^2)}{4Jf\pi^2} \quad (7)$$

$$\dot{P}_c = \frac{P_c^o \cdot [Loading - (f - f_o)/(Rf_o)] - P_c}{T_{gen}} \quad (8)$$

384 where P_c and P_{WF} are the actual conventional and wind power generation, re-
 385 spectively, P_L is the total main load and *Loading* (e.g. 95% of P_c^o in this paper)
 386 signifies the P_c output set-point under normal (pre-event) operating conditions
 387 (i.e. 5.32 GW), whereas f_o is the nominal grid frequency (e.g. 50-Hz). The wind
 388 installed capacity is assumed to be 35% of P_c^o with a 50% WF capacity factor.

389 The WF is represented by an aggregate WTG of an equivalent capacity of
 390 the WF, and facing a unified WS pattern. This does not compromise the level
 391 of details of the applied test system as the aggregate models include the essen-
 392 tial electromechanical components of the wind energy system. This aggregation

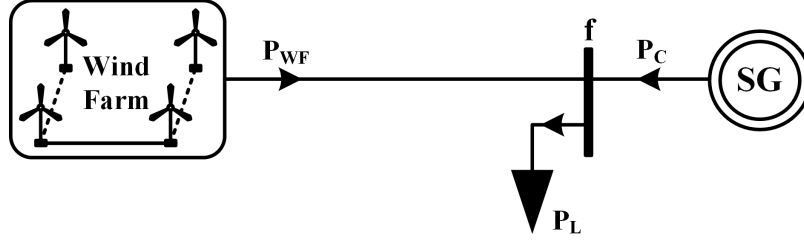


Figure 10: Conceptual representation of the implemented benchmark.

approach is used to achieve relatively high penetration level of wind power into the test power system avoiding the additional computational efforts to model and simulate each wind turbine and its incident wind speed separately. The remaining model specifications are enlisted in Table 2. To retain consistency throughout the paper authors have opted that the inertia constant in these units to comply with the detailed modelling of the synchronous AC area which is described in (7) and (8), thus inertia of the system in seconds is analysed in the next section.

Table 2: The parameters of the aggregate synchronous area

Conventional generation capacity (P_c^o)	5.6 GW
Generation time constant (T_{gen})	2 s
Lumped moment of inertia (J)	0.39 M.kg.m ²
Generation droop (R)	0.06
Damping ratio (D_g)	95
Load frequency sensitivity ratio (D_l)	1%

399

400 The system dynamic inertia constant (H_d) is estimated during the critical
401 stages of the frequency event using the following expression:

402

$$H_d = \frac{f_o}{2f} \cdot \frac{\Delta P}{P_c + P_{WF}} \quad (9)$$

403 providing that $\dot{f} \leq -0.1$ Hz/s and $f < f_o$ with ΔP denoting the instantaneous
 404 mismatch between generation and demand. The dynamic inertia is actually the in-
 405 ertia constant of the system captured at different time points during the frequency
 406 event. The system inertia under high penetration of wind energy is highly variable,
 407 so it is indicative to analyse the impact of WFs a provider of frequency support
 408 on system inertia including the turbine WTG technology and the adopted support
 409 method. This confirms the reasonable and expansive nature of the presented study
 410 in this paper, where (H_d) is calculated using (9) given that the system frequency is
 411 outside the deadband and experiencing a high rate of decay of 0.2 Hz/s or worse.

412 *5.1. Considered Operating Scenarios*

413 In each of the five case studies being examined, the system has suffered a seri-
 414 ous frequency drop caused by a sudden loss of 12% of the conventional generation
 415 capacity, namely 672 MW at $t = 10$ s time instant. The lost generation is gradually
 416 recovered at $t = 40$ s with a gradient of 2% per second to mimic the secondary re-
 417 sponse of SGs, and to test the compatibility of the applied support methods when
 418 the frequency rebounds to the safe margin. In order to isolate the effects of the
 419 support method and the type of machine, the WS is assumed constant at around
 420 8 m/s during the frequency event. This assumption is acceptable because the fre-
 421 quency transients should normally last no more than 10-30 s according to most
 422 grid codes [3]. Over such a short interval, and due to the heavy WTG inertia,
 423 many studies are based on the average WS conditions [40].

424 *5.2. Results and Discussions*

425 Fig. 11 shows that the frequency nadir has improved by about 0.25 Hz for the
 426 de-loading method and 0.15 Hz for the KE extraction counterpart. It can also be

427 seen that the superior performance can be achieved with the de-loading approach
 428 as the down-pitching recaps the higher output for a power surge compared to the
 429 extracted energy at the selected K_{ex} . The frequency excursion clearance after the
 430 recovery of the lost generation is smooth without any spikes or overshoots due
 431 to the developed droop controller action, which regulates the supportive power
 432 surge through the droop constants (i.e. D_F and K_{ex}) based on the frequency drop
 433 severity. It is worth mentioning that the provided WF support reduces the RoCoF
 434 during the critical early stage of the event. This is important in order to avoid
 435 any unnecessary tripping of the RoCoF relays of SGs if the pre-set threshold (e.g.
 436 typically from 0.5 Hz/s to 1 Hz/s during the first 500 ms) is violated according to
 437 the grid code [39].

438 Differences brought by the two WTGs are fairly small because of the pre-
 439 dominant power system dynamics over the WTG mechanical and aerodynamics
 440 effects. The WTG decelerates and recovers to the nominal speed at lower rates
 441 using the BDFRG, which coincides with the results obtained in Section 3. How-
 442 ever, the maximum rotor speed deviation from its nominal value does not exceed
 443 2%. The BDFRG appears to be more resistant to speed changes in case of droop
 444 de-loading, which counts as a merit in its own right.

445 The WTGs power surges are almost identical for the two methods. Still, the
 446 DFIG appears to be advantageous in this sense as detailed in the zoomed window
 447 of the power plot in Fig. 11. The WTG decelerates during the KE extraction until
 448 reaching a lower speed, as depicted in Fig. 11, which corresponds to the incident
 449 frequency variation given the predetermined value of K_{ex} . In this case study,
 450 the frequency drop is less than $f_{drop_{max}}$, which helps the WTG not to attain the
 451 minimum allowed rotor speed. Hence, the WTG continues to operate at the lower

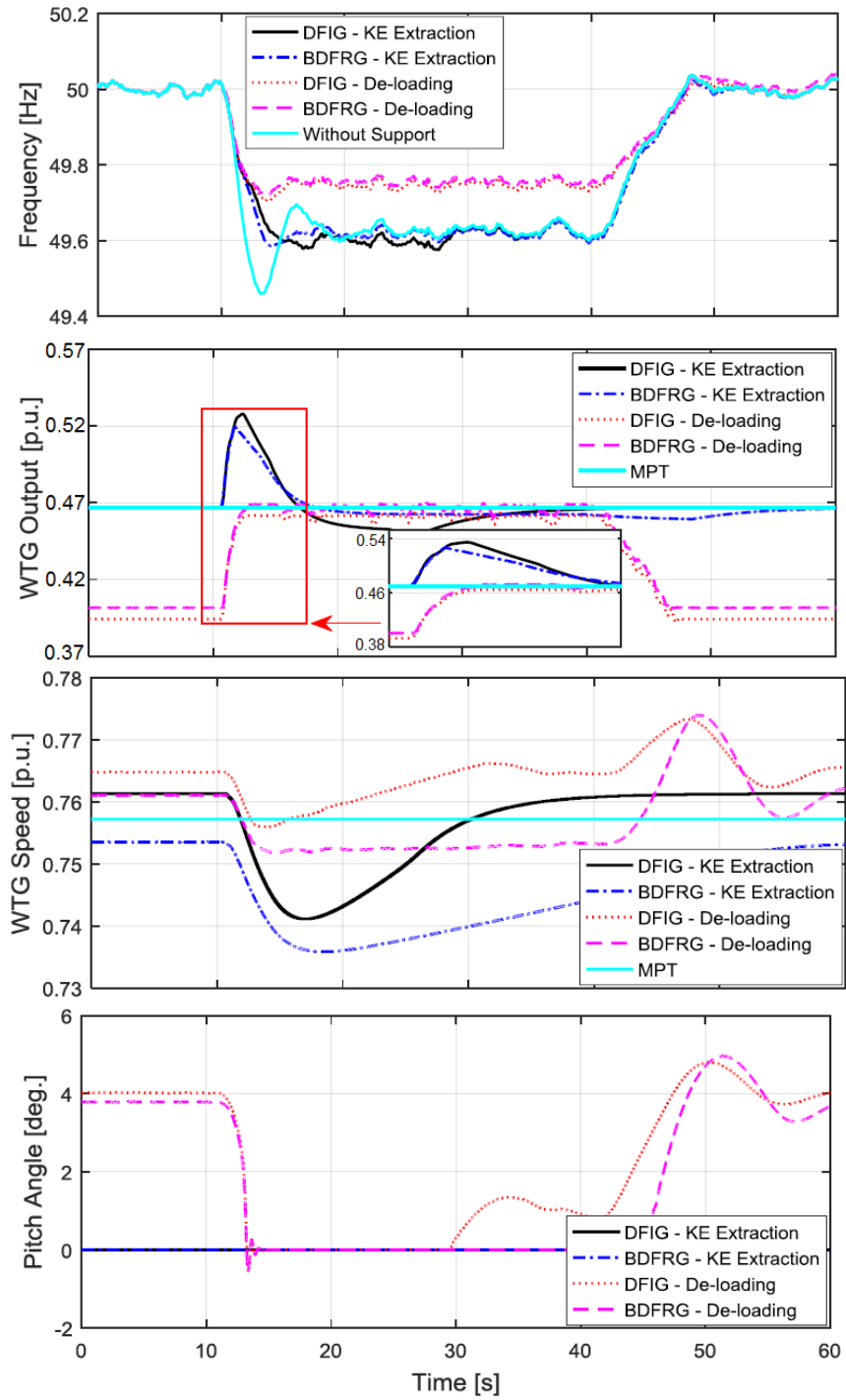


Figure 11: WTGs response using the proposed frequency support methods at fixed wind speed.

452 speed without the need to recover until the frequency starts building up to reach
 453 the safe margin. The power surge sustained for about 10 s, and the recovery to
 454 the nominal speed was slower for the BDFRG. The de-loading technique shows a
 455 little impact on the WTG speed due to the WTG aerodynamics, mostly during the
 456 pitching down as a small portion of the injected power accelerates the WTG, this
 457 being limited in the BDFRG case. On the other hand, the DFIG pitching is ahead
 458 of the BDFRG's as shown in Fig. 11.

459 The H_d changes during the considered frequency scenario are presented in
 460 Fig. 12. It can be seen that the H_d estimates have somewhat increased in all
 461 the cases. The BDFRG achieved an extended rise of about 0.4 s relative to the
 462 DFIG, which could be explained by its slightly faster response to the T_m variations
 463 through the pitching process. Generally, the H_d improvements are marginal (i.e.
 464 0.1 s to 0.3 s) during the critical period from $t = 10$ s up to 17 s. The frequency
 465 starts building up to its nominal value at $t = 40$ s (Fig. 11), when the inertia drops
 466 by 0.15 s at $t = 44$ s as zoomed in the right-sided window of Fig. 12, which
 467 may be attributed to the BDFRG slower rotor speed recovery and the extended
 468 time required for the WTG to reach its nominal output for a given WS. Hence,
 469 the power imbalance is diminished after a slight delay reflecting upon the H_d
 470 reduction according to (9). However, the inertia drop is about 5% of the average
 471 value (≈ 3 s). In addition, the overall system inertia is reduced compared to the
 472 early stage of the event (i.e. after $t = 10$ s).

473 Note that H_d is evaluated using (9), and denoted accordingly in Fig. 12, only
 474 if there is a power mismatch (i.e. generation less than demand causing a negative
 475 RoCoF). Else, when a H_d value is not displayed this implies an improvement as
 476 illustrated for $t \in [10-15]$ s, where $H_d \approx 4$ s, while cases with frequency support

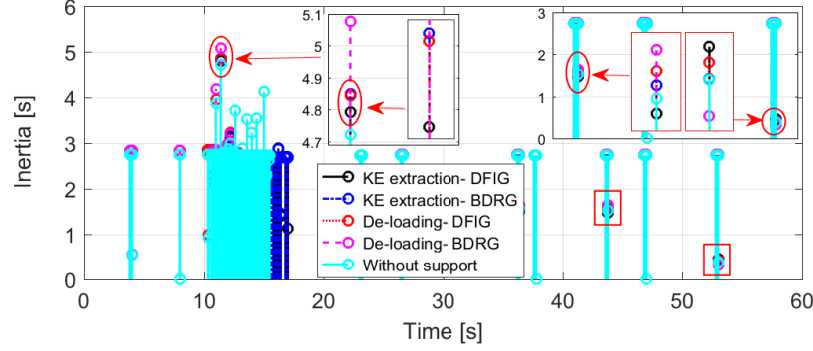


Figure 12: The system dynamic inertia constant during the early and recovery stages of the implied frequency event.

do not return a value. Conversely, at $t \in [16-17]$ s, the KE extraction returns a relatively lower H_d , mainly for the BDFRG as discussed above, and the case without support does not give any value in this time interval.

The qualitative properties of the two WTGs in the context of frequency support provision are summarised in Table 3.

Table 3: Relative advantages (+) and limitations (-) of the WTGs

Frequency Support Indicator	DFIG	BDFRG
De-loading pitch angle	(-) Higher	(+) Lower
KE extraction rotor speed recovery	(+) Faster	(-) Slower
Extractable KE	(-) Less	(+) More
Power system dynamic inertia	(-) Reduced	(+) Improved

6. Conclusions

This paper has made a comprehensive multi-dimensional comparison of two frequency support methods, the KE extraction and pitch de-loading, individually applied to the closely related WTG types, the conventional DFIG and evolving

486 BDFRG. The major contributions of the work are therefore manifold and not only
487 limited to comparing the integrated generator technologies for a given frequency
488 regulation technique as its main focus, but also the other way around. The consid-
489 ered concepts have shown to play a pivotal role in the power injection during the
490 frequency transient and the WTG post-incident restoration of normal operation.
491 The KE extraction has allowed a somewhat faster DFIG recovery response than
492 BDFRG's, while both WTGs are able to offer similar de-loading performance,
493 with slightly mitigated pitch angle variations in the BDFRG case, which are fa-
494 vorable to the pitch actuators.

495 The frequency studies have indicated discrepancies between the WTGs, that
496 largely depend on the ratio of the actual wind power penetration level to load
497 demand at the inception of frequency disturbance event and the support method-
498 ology in question. The dynamic inertia evaluation has confirmed the merit of pitch
499 de-loading approach by the absence of both adverse implications and reliance on
500 the drive train inertia. The results presented are encouraging and have undoubt-
501 edly shown that the BDFRG can be rather competitive with the commercial DFIG
502 of the same rating in terms of frequency support abilities to warrant further inves-
503 tigations as a promising brushless candidate for wind power applications.

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